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ABSTRACT

In contrast to the conventional rotational compressors, the linear compressor is driven by a linear motor directly coupled with a piston. So the performance of the linear compressor is strongly dependent on the characteristics of the linear motor. In addition to high efficiency, the parameters of a linear motor should be nearly constant regardless of the amount of the current flow and position of the piston in order to control the position of piston without an additional sensor. And high reliability of the linear motors is required for use in compressor operated under severe conditions for long period. Several types of the linear motors are investigated to meet those requirements. A simple structure of moving magnet motor was designed for its high power density and efficiency. Analysis and experiments show the linear motor is reliable enough and has efficiency of more than 95%.

INTRODUCTION

An Efficient compressor for the refrigerators is highly required in recent years. A refrigerator consumes 20~40% of the total electric energy in a house. And most of the electricity in the refrigerator is consumed for operating compressor [1]. Many countries set guidelines for energy consumption and demand higher energy efficient appliances to meet the guidelines that become tougher year by year. LG Electronics has developed an energy efficient linear compressor for the household refrigerators utilizing a free piston mechanism. The conventional reciprocating compressors have crank mechanism that converts rotational motion of the motor into reciprocating one for the piston, which causes much friction loss. The linear compressor is composed of a linear oscillating motor directly coupled with a piston and springs for resonant operation.

The linear motors for the compressors should satisfy the following requirements,

- High efficiency and compact size for the efficiency of the compressor with the conventional chamber size.
- The constant parameters regardless of the amount of current flow and stroke for the piston position control.
- High reliability for long life essentially expected in the household refrigerators.

The analysis and experiment results of a linear motor to meet those requirements are presented in this paper.

CONFIGURATION OF LINEAR MOTOR

The criteria of practical choice among the various types of linear motors are efficiency and size. The moving coil motors are easy to design and to control the stroke. However they require large amount of permanent magnet to achieve high efficiency. And big size of the moving coil motor due to its low power density makes it difficult to be adopted for the compressors of household refrigerators. Several types of the moving coil motor are being use in the small compressors for the portable refrigerators. Moving iron motors are cheap due to the absence of the expensive

magnets however they have very low efficiency. The recent development of high-energy permanent magnets-such as NdFeB - helps design moving magnet types of linear motors efficient and compact. Because of high magnetic flux density of NdFeB, the moving magnet motors can generate enough force with small amount of magnets. So the moving mass is much lighter compared to that of other types of motors. Small moving mass means ease to design the springs for the resonance operation of the linear compressor. Therefore the moving magnet type is major trend for the high-power rate of linear motors

Fig.1 shows the configuration of the Redlich type of the linear motor we have chosen among many topologies of the moving magnet motors. Stator is divided into outer and inner one by the moving magnets embedded in a rigid frame. The stators are laminated in the radial direction to reduce eddy current loss. A ring-shaped coil is installed inside the outer stator [3].

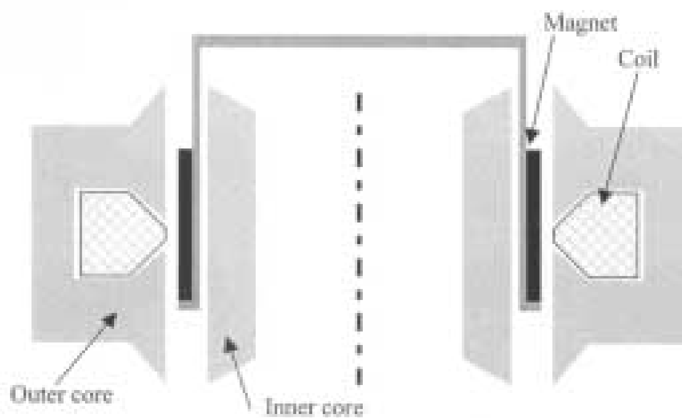
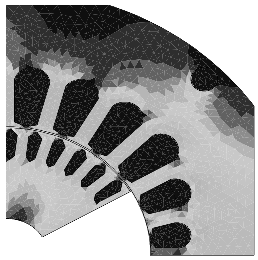


Fig.1 Schematic Diagram of Linear Motor in the Compressor

EFFICIENCY AND SIZE

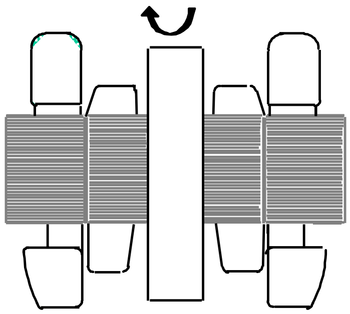
The size of a motor is directly proportional to the required force (or torque). High speed with low force is recommended to design a motor small. In the conventional compressors where high-speed rotary motors are used, the torque to the piston is amplified as much as the crankshaft reduces the speed. However, the linear motor directly drives the piston with low speed - short stroke at the frequency of 60Hz or 50Hz. So the high force is required for the piston that results in big size of the motor. Usually speed of the rotary motor is about three times as high as that of the linear motor in the compressors. Single-phase induction motors or ferrite magnet-embedded electrically commutated motors are typically used in the conventional compressors. The magnetic flux of NdFeB magnets is three times as much as that of the ferrite; dimensions of the moving magnet linear motor can be kept almost same as those of the conventional motors.

High efficiency of the linear motor comes from a design of great simplicity of magnetic circuit. The rotary motors have multiple coils in the stator in which many slots are for inserting the coils. Magnetic flux is partly saturated around teeth and yokes (Fig.2a); so much iron loss is generated due to high flux density and harmonic flux in the stator. And rotary motors have end coils on each end of the stator (Fig.2c). The volume of these useless end coils is about twice as much as those of inside slots. The linear motor has only one slot for the coil (Fig.2d). It is easy to design the shape of the stator core in order to avoid the magnetic flux saturation without increasing overall motor size. The distribution of the magnetic flux in the stator is almost uniform (Fig.2 b). Because the linear motor has one coil, it is easy to increase the space factor of the coil to get lower current density.

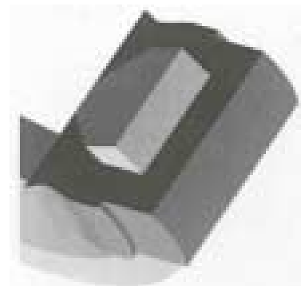


(a) Flux Distribution of Induction Motor

(b) Flux Distribution of Linear Motor



(c) End Coils in Induction Motor



(d) Concentration Coil

Fig. 2 Comparison of Rotational Motor and Linear Motor

Efficiency of the linear motor can be directly measured with a linear dynamometer in Fig 3. Amplitude of magnet motion is measured with the displacement sensor attached on the load generator. And the force generated from the tested motor is measured with the force transducer installed between the generator and the tested motor [4]. Output power is calculated with the measured values from the displacement sensor and force transducer.

In the resonant condition, the experimental results show the efficiency of the developed linear motor reaches 95% at normal temperature (Fig.4). Fig 5 shows the linear motor generates much less copper loss and iron loss under the same rated power. It is worth of noting that the efficiency is maintained over the wide range of power levels, especially at low power levels. This can be important in refrigeration compressors. The motor current increases by the reactive force when the motor is operated out of the resonance.

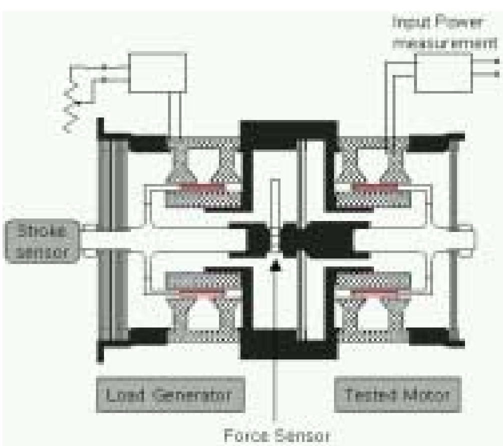


Fig 4. Linear dynamometer

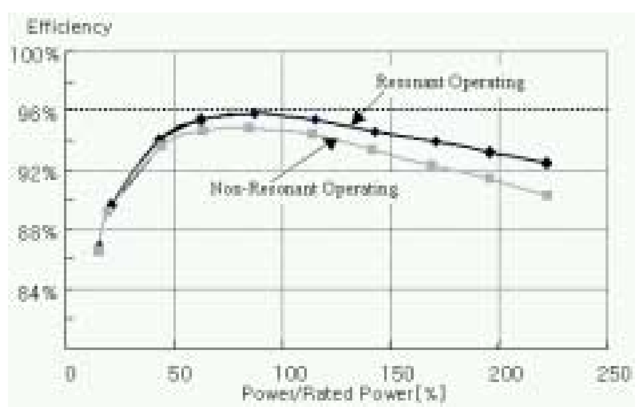


Fig.5 Experimental Results of Motor Efficiency

Fig.3 Loss Comparison between Rotational and Linear Motor

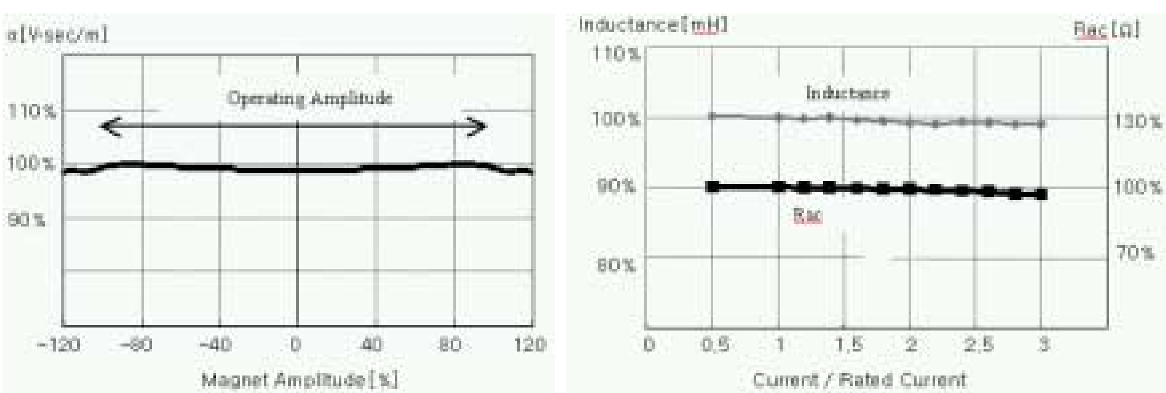
MOTOR PARAMETERS FOR SENSORLESS POSITION CONTROL

The amplitude of the piston is mechanically determined by the crankshaft in the conventional compressors. However the linear compressors have free piston mechanisms, so the amplitude of the piston is varied by the load condition. Since the performance of the compressors is sensitive to the top clearance -- distance between discharge valve and top position of the position when compressing the refrigerant, the top position of the piston must be precisely controlled by an external drive. Many position sensor equipped feedback control methods are available. However installing sensors inside the compressors may not be the practical way due to reliability and cost of the sensors. In the developed linear compressor, the information of the piston position can be calculated by measuring applied voltage and current flow by the equation (1).

$$Stroke = \frac{1}{\alpha}\int (V - Rac\,\mathbf{i} - L\frac{d\mathbf{i}}{dt})dt \;------------------ (1)$$

where; α : Motor constant [N/A, Vsec/m], Rac: AC resistance of the linear motor [Ω], L: inductance [H]

Motor parameters--motor constant, Rac and inductance--must be constant within the determined current and stroke range. Rac represents losses by the current flow including iron loss generated in the parts surrounded by the coil. Magnet, stator core and pole shape in particular should be carefully designed to make such parameters constant. Experimental results in Fig.6 show the motor parameters are independent of the magnet position and of the current over the operating region. Motor constant is constant when the magnets oscillating on the operating region at a frequency. The parameter declines slightly when the magnets approach the edges of the stator poles (Fig.6a). The Rac and inductance are constant regardless of the amount of the current on the operating region (Fig.6b). The variance in each parameter is negligible. This means the linear motor itself can be operated as a sensor as well.



(a) Motor Constant vs. Magnet Position

(b) Rac, L vs. Current flow

Fig. 6 Parameter Characteristics of the Linear Motor

RELIABILITY

The linear motor must maintain high reliability in the long period. The average life of the compressors in the refrigerators is more than 10 years even in any severe operating conditions. In order to operate over its life-long period, the linear motor should pass the same reliability tests that are commonly applied to the conventional rotary motors. Moreover, the linear motor must satisfy another requirements of the reliability due to its unique characteristics -- the resonant operation and the use of the permanent magnets. If the linear compressor is not driven with a variable frequency controller, such as inverter, the pressure in discharge and suction area may vary widely according to the load condition of the refrigerator, which might cause the linear compressor operated out of the resonance. In such case, the reactive power increases as the linear motor is operating away from the resonant point. As a result, the effective output power of the motor does not increase as much as input does. This may cause failure in compressor operation and shorten the life of the motor. Thus the linear motor must be designed to stand over the certain operating range around specific resonant point.

The test results of the pull-down test in Fig. 7 shows the developed linear motor operates without trouble. This pull-down test at 43℃ ambient temperature is considered as the maximum load condition in the operating ranges of the refrigerator. The abrupt increase of input power as in the conventional compressors does not occur in the linear compressor because of the high efficiency of the linear motor over the wide range of power levels.

The linear motor must allow a large air gap between stators (Fig. 1) to provide space for the magnet motion. Thus it has low permeability coefficient, compared to that of the rotational permanent magnet motors. Demagnetization of the permanent magnets should be taken into account when designing the linear motor because it has the low permanent magnetic circuit exposed in high temperature and large current flow under the compressors operating conditions. With the help of brilliant development of high-energy NdFeB magnets, the magnet in the developed linear motor gained enough margin from being demagnetized (Fig.8).

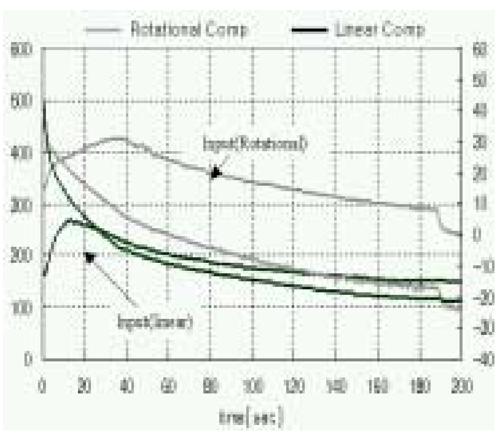


Fig.7 Pull-down Test results of a Refrigerator at 43℃

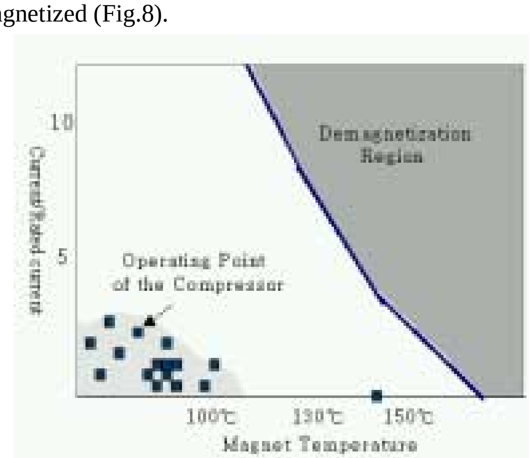


Fig.8 Test results of Demagnetization Boundary

PERFORMANCE OF LINEAR MOTOR IN COMPRESSOR

With the high efficient linear motor plus the superior tribological advantage of the free piston mechanism, the LG linear compressor achieved 20~30% more efficiency than the most efficient current reciprocating compressor. With the refrigerant of R143a, the energy consumption of a 680 liters top-mount refrigerator was reduced by 24% in drop-in replacement of the linear compressor. The reduction of 47% has been achieved with some additional

modification of the refrigerator. If the cooling capacity of the linear compressor is modulated, the additional reduction will be achieved [1]. With the refrigerant of R600a, the energy consumption of 300 liters top mount European refrigerator was reduced by 25% in drop-in replacement of the linear compressor.

CONCLUSION

Cost, size and efficiency are obviously considered in designing the linear motor. And the mass of the moving part in the linear motors is also considered for the ease of the resonant spring and the cost especially in the moving magnet type. For the mass production, cost and manufacturability are specially emphasized to break the market barriers. All requirements for the linear motor will be fully fulfilled when the motor structure is as simple as possible. An example of the linear motor to meet those needs was suggested in this paper. The linear motor, having superior efficiency to the rotary motors, was able to be used as a sensor as well due to its constant parameters and was confirmed in aspect of the reliability.

The energy efficiency of the linear compressors with various refrigerants convinces the usefulness of the linear motors with various refrigerants. These technologies of the linear motor can extend the horizon of the application to the linear compressors for air conditioners, cryocoolers and the other types of cooling devices.

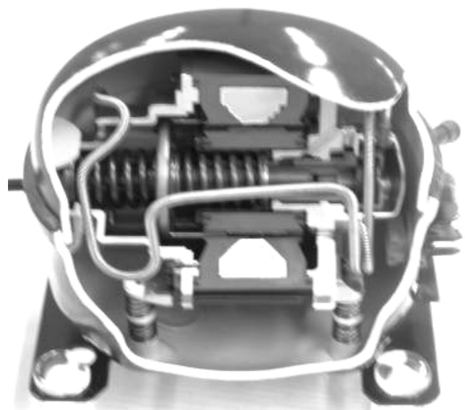


Fig. 9 A Developed Linear Compressor for R134a

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